ORIGINAL ARTICLE

Proof of Concept Study For Using UR10 Robot To Help Total Hip Replacement

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Abstract

Background: The demand for total hip replacement (THR) for treating osteoarthritis has grown substantially worldwide. The existing robotic systems used in THR are invasive and costly. This study aims to develop a less-invasive and low-cost robotic system to assist THR surgery.

Methods: A preliminary robotic reaming system was developed based on a UR10 robot equipped with a reamer to cut acetabulum. A novel approach was proposed to cut through a 5mm hole in femur such that the operation is less invasive to the patients.

Results: The average error of the cutting hemisphere by the robotic reaming system is 0.1182 mm which is smaller than the average result reaming by hand (0.1301 mm)

Conclusion: The robotic reaming can help make THR procedures less invasive and more accurate. Moreover, the system is expected to be significantly less expensive than the robotic systems available in the market at present.

KEYWORDS
Total hip replacement (THR), UR10 robot, robotic-assisted surgery

1 | INTRODUCTION

Osteoarthritis (OA), often referred to as “wear and tear” arthritis, age related arthritis or degenerative joint disease, is the most common form of joint disorder. The hip joint is one of the body's largest weight bearing joints, only secondary to the knee joint, and is commonly affected by OA[1]. The current accepted understanding of hip OA process involves progressive loss of articular cartilage, subchondral cysts, osteophyte formation, periarticular ligamentous laxity, muscle weakness and synovial inflammation[2]. Men have higher prevalence of hip OA before age 50, whereas woman have higher prevalence thereafter[3]. Caucasian populations have a higher risk of hip OA which ranges between 3% and 6% as compared with 1% or less in Asians, East Indians and native Americans[4].

In Australia, increasing levels of obesity, population ageing and growth in sports related injuries all are anticipated to manifest in a greater future burden of OA[5]. The number of total knee replacement (TKR) and total hip replacement (THR) procedures has grown steadily over the last two decades in Australia and other developed countries[6]. Moreover, studies have reported a 105% increase in primary TKR and 73% increase in THR over a 10 years period (2003-2013) in Australia. In the next couple of years, there will be an exponential rise in the number of THR and TKR procedures in Australia which is based on recent growth. The incidence of TKR and THR for OA is estimated to rise by 276% and 208% respectively, by 2030[6].

An increasing burden of joint replacement surgery has significant cost and health workforce implications. The cost of a TKR or THR in Australia is estimated at $AUD 19,000 to $AUD 30,000 per patient, with over $AUD 1.2 billion spent annually in Australia on OA-related hospital admission[6]. Moreover, the use of robotic assisted surgery further adds on to the cost of the procedure by approximately $AUD 1000 per case. A long term solution to address this overwhelming burden on economics and reduce the financial cost of the treatment, and at the same time improve the accuracy and clinical outcomes of surgery is to develop a less expensive robotic system, which is one of the main purposes of this research.

Currently, most of the THR operations are now performed by surgeons using manual instruments. There are several surgical approaches for hip replacements, such as posterior, lateral, anterior, and superior, all with their own advantages and disadvantages[7]. The superior approach as the name suggests approaches the joint from the superior or proximal to the joint. It uses the anatomical plane between the abductor muscles and external rotators. The theoretical advantages of this approach are that it spares any muscle cutting therefore is less invasive and has a quicker recovery and less risk of dislocation. The superior approach is popularised as supercapsular percutaneously assisted (SuperPath) approach in total hip arthroplasty marketed by microport orthopaedics. While this approach still requires reaming of the acetabulum using a specialised aiming device with anterior retraction of the femur. To insert the acetabular reamer into the joint also requires a skilled assistant with a degree of force to move the femur out of the way. Moreover, modifications of this approach use an angled reamer coming in from above. The problem with these reamers is that they are quite bulky and the direction of the reaming force is not in line with the alignment of the acetabular cup.

To overcome these potential difficulties, a new technique under development by the primary author is performed by drilling a small hole into the lateral cortex of the femur with the femur sitting in its natural non dislocated position and using a C-arm outrigger to apply the force to ream the acetabulum (Fig. 1). The advantage of this approach is that the femur does not have to be moved out of the way or retracted to perform the acetabular cutting which reduces the trauma or soft tissue damage required with routine hip approaches. That is, it needs no displacement away from the acetabulum as it is a direct line. It also requires minimal work from the assistant. The hole is spanned by the prosthesis once the surgery is completed (Fig. 1: Right). This hole has been studied using finite element analysis and has shown not to weaken the bone. This novel less invasive approach provides an excellent adjunct for introduction and development of a universal and less expensive robotic system. The development of such a robotic system incorporating this new approach is the main emphasis of this research.

Decades ago robotic surgery was an evolving concept, but with the rapid progress of science and technology, the concept has become a reality and achieved great success in clinical practice. MAKO robot[8] is currently the most advanced robotic systems for THR which improves the earlier version robotic systems[9] such as Robodoc[10]. The main benefits of robotic-assisted surgery include enhanced and accurate surgical planning, precise component positioning, better soft tissue

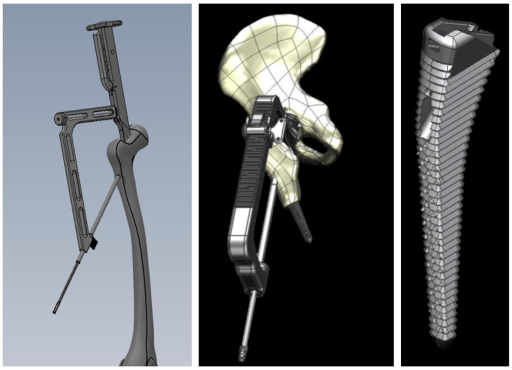

FIGURE 1 Novel idea for less invasive cutting through femur. Left: Aiming device to drill hole in lateral femur; Middle: Reamer rod going through lateral cortex and C arm; Right: Broach with lateral hole.

tensioning and balance, and restoration of limb length and offset[11]. Currently robotic arthroplasty represents only 5% - 7% of overall cases, the main reason being potentially the high cost of performing the procedure and capital outlay.

This paper presents the design, development and test of a robotic reaming system to perform a safe and highly accurate preparation of the acetabulum using a reamer with the novel less invasive approach. Moreover, the system is expected to be significantly less expensive than the robotic systems available in the market at present.

2 | OVERALL SYSTEM DESIGN

The robotic reamer system, shown in Fig. 2, consists of a collaborative robotic manipulator, a custom end-effector, and transportable mounting solution. With the reamer attached to the end-effector, the system can perform cutting the hemisphere in acetabulum autonomously or semi-automously according to surgeon or regulatory requirements and is suitable for the novel less invasive approach.

2.1 | Collaborative Manipulator

At the core of the system is UR10 collaborative manipulator from Universal Robots. The UR10 was chosen as it was certified for safe physical human-robot interaction and is at least 10 times less expensive than the robotic system available in the market at present, MAKO. UR10 is safe to work with human since it has emergency stop when velocity or force encountered by the robot is larger than a threshold. Additionally, the 10kg payload capacity was large enough to support the type of total hip replacement being considered. Another factor in choosing the UR10 was the 1.3m reach, which is larger than most comparable collaborative robots[12]. The larger reach provides the surgeons with a larger workplace to work with. The operating space during the surgery is of course very important for the surgeons.

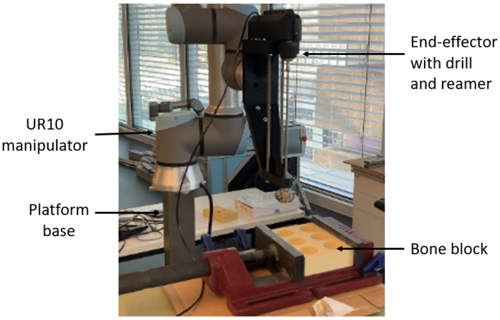

FIGURE 2 A version of the robotics reamer system.

2.2 | End-effector

To facilitate cutting smooth hemisphere in acetabulum, a custom end-effector was developed. Design of the end-effector was guided by the developing surgeon, with several iterations tested. The final design shown in Fig. 3, allows for the novel less invasive approach. A C-Arm with mounting capabilities for reamer was developed to apply the proposed less invasive approach. In order to be able to install a 90-degree angle drill to the C-Arm, the drill was disassembled and a new enclosure was designed. A sterile offset was designed which is required to maintain a distance between the C-Arm to the robot end-effector. This structure can also ensure that the robot can be sterilized easily. The battery and switch was detached away from the drill to allow for the operator to decide when the drill should be on. This drill alters the speed based on button press which changes supplied voltage from 0v to 20v.

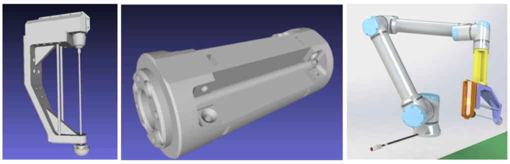

FIGURE 3 Left: C-arm for robotic reaming system, Middle: Sterile Offset, Right: The structure of the robot reaming system with end-effector.

2.3 | Patient and Surgeon Safety

A critical requirement of any collaborative robot system is maintaining the safety of the human operator. This facet was considered in all design aspects of the robotic reamer system. The UR10[12] is a collaborative robot designed to meet standards regarding physical human robot interaction. Commands that are sent to the UR10 controller for execution are subject to maximum force, speed, energy and other limitations set by these standards.

As a robot system used in hip replacement surgery, ensuring the safety of patients is the top priority. Current research studies exploring bone removal using the reamer show high temperatures involved during the surgical procedure that could potentially lead to necrosis[13] [14].The recommended speed of the reamer is usually between 250 and 500 revolutions per minute (RPM)[15]. Therefore, The designed drill can alter the speed based on button press and the maximum rotating speed is set to 280 RPM. During the cutting process, the force exerted by the reamer on the patient's bone is always monitored. Once the maximum force exceeds the set threshold (such as a sudden large displacement of the patient), the robot will stop working immediately.

3 | CONTROL ARCHITECTURE

This robotic reaming system mainly includes two core control systems, one is the admittance control for physical human-robot interaction and calibration stage, another one is the position control for the cutting process.

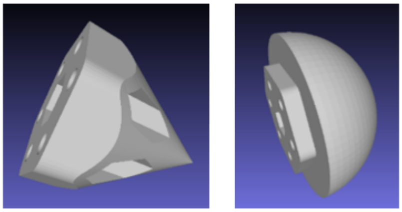

FIGURE 4 Left: Calibration Pointer, Right: Hemispherical Calibration Tool.

3.1 | Calibration through admittance control

Smooth interaction between the surgeon and the robotic reaming system was achieved using an admittance control scheme based on[16]. Suppose the force $\mathbf{F}$ represents the surgeon intention. They are multiplied by admittance matrix $\mathbf{K}$ to generate Cartesian velocity command $\dot{x} = \mathbf{K} \cdot \mathbf{F}$. The Cartesian velocities are transformed to joint velocities $\dot{x}$ using the inverse Jacobian matrix, which are then sent to the Universal Robot controller as joint velocity commands.

Calibration tools as shown in Fig. 4 were designed to identify the anatomical landmarks of the acetabulum and locate the centre of the hemisphere accurately before the cutting adjusted to the preoperative plan. Since the acetabulum is usually a hemispherical concave structure, the hemispherical calibration tool (Fig. 4 Right) was designed to put into the acetabulum. By adjusting the hemispherical device as far as possible to fit the acetabulum, it can be determined that the centre of the hemispherical device is the centre of the acetabulum. This centre is then the starting point of the centre of rotation of the hip. While in some cases, for example, the acetabular fossa of patient is too shallow, the error of using the hemispherical calibration tool will be too large. Then the calibration pointer (Fig. 4 Left) can be applied to touch the surface of the bone and select several points (Fig. 5). The selected points was then used to fit a hemisphere in order to find the centre. Admittance control was implemented on the UR10 robot with a joystick acting as a dead-man switch during the calibration process such that the robot can move freely under the control of human hands. A slower speed was used such that a more fine movement can be achieved to locate the acetabulum with higher accuracy.

FIGURE 5 Calibration process: using the calibration pointer to touch the surface of acetabulum and select several points. The selected points is used to fit a hemisphere and determine the centre.

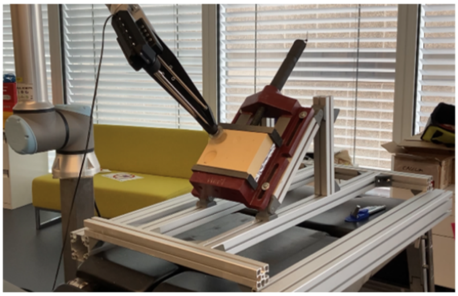

FIGURE 6 Experimental Setup of Robotic Reaming System: bone blocks with different densities (#30 and #15) were fixed on a surgical table by a vise and cut by the robotic system, and the aluminum alloy structure can change the angle between the bone block and the table.

3.2 | Autonomously cutting through position control

The control algorithm implemented on the UR10 robot is position control during the cutting process. This type of control can specify the global positions for the robot end-effector to follow such that the robot can cut the required shape. The relative position between the reamer and the robot end-effector needs to be accurately calibrated such that the trajectory of the robot end-effector can be executed to correctly cut the required hemisphere.

4 | TESTING AND EVALUATION RESULTS

This section will show that the proposed robotic reaming system based on UR10 has the potential to help the total hip replacement by cutting a smooth hemisphere in acetabulum autonomously.

4.1 | Experimental setup

To simulate the real operation situation, the surgical table was used for the experiments. A new structure to fix the bone block on the surgical table was implemented and it has been able to ensure that the bone block can be moved to different angular positions. A series of practical experiments were performed to evaluate the performance of the robotic reaming system under realistic scenarios. The experimental setup is shown in Fig. 6.

A number of hemispheres have been cut from the bone blocks with different densities using the robotic reaming system. The bone blocks used were closed foam cells conforms to ASTM F1839-08 Standard Specification for Rigid Polyurethane Foam, from Pacific Research company USA. Foam blocks are used in many in vitro studies instead of cadaveric bone because they are readily available and have constant mechanical properties. Two different densities (#30 and #15) were used to simulate normal and osteoporotic bone. Bone block #30 has a density of 30 pcf or 0.80 g/cc. Bone block #15 has a density of 15 pcf or 0.24 g/cc.

In order to obtain more convincing statistics, multi-size hemispherical cuts were performed on bone blocks with the two different densities. The cutting diameters used include 48 mm, 50 mm, and 52 mm, which are determined according to the sizes of the reamers. These parameters are based on actual surgical experience being the commonest reamers used in surgery. The experiment using the same parameters (density of bone block, cutting diameter, reaming by the robot or manually) was repeated ten times. The cut hemispheres were scanned using Solutionix C500 such that quantitative comparisons on the accuracy can be made. Some examples of the cut bone blocks and their 3D scans are shown in Fig. 7

4.2 | Accuracy assessment

The aim of the robotic reaming system is producing the cut surface which matches the required hemisphere as accurate as possible. Therefore, the point cloud of the cut surface generating by 3D scanner was used to fit a perfect sphere with a radius that is the same as the target hemisphere. Then the fitting centre of the cut surface can be obtained. Finally, the difference between the distances from the point cloud to the fitting centre and the target radius was used to evaluate the accuracy. Suppose the radius of target hemisphere is r, the centre of cut surface is $\mathbf{C} = [C_x, C_y, C_z]^\intercal$, then $\mathbf{C}$ should satisfy the following cost function:

$$\underset{C_x,C_y,C_z}{\text{argmin}}\ F = \sum_{i=1}^{M} \left((C_x - x_i)^2 + (C_y - y_i)^2 + (C_z - z_i)^2 - r^2 \right)^2 \tag{1}$$

M is the number of points on the cut surface and $[x_i, y_i, z_i]^\intercal$ is the coordinate of the ith point. Then the error of the ith point can be defined by

$$Error_i = \left| \sqrt{(C_x - x_i)^2 + (C_y - y_i)^2 + (C_z - z_i)^2} - r \right| \tag{2}$$

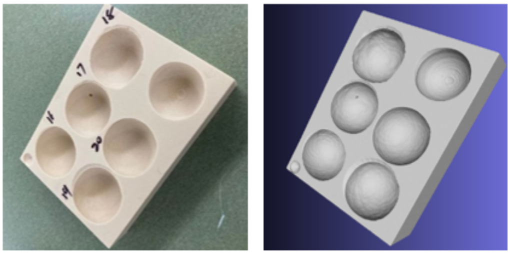

FIGURE 7 examples of the cut hemispheres on the bone blocks and the 3D Scan of the results for quantitative comparison.

TABLE 1 Experiment Setup and Results

Exp	Density	Exp Type	Maximum Error [mm]	Average Error [mm]
1	#15	Reaming by Robot	1.0155	0.1182
2	#15	Reaming by Hand	1.1932	0.1301
3	#30	Reaming by Robot	0.7935	0.2554
4	#30	Reaming by Hand	1.3269	0.2537

For the cut hemisphere of each experiment, we compute the errors of each point through Equation (2), and then calculate the maximum error and average error. Tab. 1 illustrates the average accuracy results of the experiments repeated 10 times. If the density of bone block is #15, the average error of the robotic system is 0.1182 mm which is smaller than the average result of reaming by hand (0.1301 mm). There is almost no difference in the average error between using a robot (0.2554 mm) and a hand (0.2537 mm) when cutting a bone block whose density is #30. Moreover, the maximum errors produced by robot cutting is always far smaller than human cutting. Therefore, the proposed robotic reaming system based on UR10 has the potential to help cut a smooth hemisphere in acetabulum autonomously.

In addition to the accuracy assessment, the average time cost to complete the cut using the robotic reaming system is 36 seconds, which is similar to that of manual reaming by surgeons. Since the robot replaces the surgeon to hold the C-arm to perform the thrust required to ream the acetabulum, the feeling to the surgeon is simply that of gentle pushing and pulling once the desired direction is set. Thus the workload of the surgeon will be saved in the future robotic reaming operation. Furthermore, combining the novel approach with some form of navigation and then taking the next step of using a robot in THR, the accuracy and simplicity of the procedure is expected to be improved significantly.

5 | CONCLUSION AND FUTURE WORK

5.1 | Conclusion

In this paper we presented a robotic reaming system using a UR10 robot which is significantly less expensive than other surgical robotic system on the market. The system can help make total hip replacement (THR) procedures less invasive and more accurate. The description in details include design, development and testing of the system to cut a smooth hemisphere in the socket of the hip bone (acetabulum). The experiment and evaluation results confirm that the development of the proposed robot reaming system for hip replacement has great feasibility and potential.

5.2 | Future work

The current robotic reaming system is only tested by cutting bone blocks, so it is necessary to perform evaluation and test using cadavers. Moreover, the UR10 robot itself has limited sensors, so it needs to rely on external sensors. It will be further developed to equip with different sensors such as electromagnetic sensors which are for developing the navigation system to clearly compute the relative pose between the robot reamer and the acetabulum. The information will be used as the feedback such that the hemisphere can be cut accurately and safely even when the patient moves. Finally, the reamer has its own limitations for cutting a smooth hemisphere. In the future, we have plans to replace the reamer with a burr and develop a robotic burring system. the UR10 robot is not a redundant manipulator so that it cannot reach certain poses easily because of singular configurations. Therefore, the trajectory design of a burr will be more complex and require more careful considerations.

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CONFLICT OF INTEREST

There are no conflicts of interest to declare.

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